

**TRIDENT DRILL VALIDATION AT MARS AND LUNAR ANALOG FIELD SITES.** B. Glass<sup>1</sup>, C. Stoker<sup>1</sup>, H. Battah<sup>1</sup>, S. Boelter<sup>2</sup>, C. Fortuin<sup>3</sup>, I. King<sup>3</sup>, T. Stevenson<sup>1</sup> and T. Stucky<sup>1</sup>. <sup>1</sup>NASA Ames Research Center, Moffett Field, CA 94035, USA, [brian.glass@nasa.gov](mailto:brian.glass@nasa.gov). <sup>2</sup>University of Minnesota, Minneapolis, MN 55455, USA. <sup>3</sup>Honeybee Robotics, Altadena, CA 91001, USA.

**Introduction:** Drilling on Earth is typically a human-intensive activity. Drilling on other planets is further complicated by the lack of prior local field surveys of their target area, hence blindly drilling into uncertain target rocks. Field conditions on the Moon or Mars are also different than for shallow drilling on Earth: lower temperatures and pressures, less power available, low masses (hence less weight-on-bit). Given the cost of transport from Earth, no drilling muds or working fluids are likely to be available to carry away cuttings. And impact-gardened regolith and dust vary mechanically and texturally from most terrestrial soils.

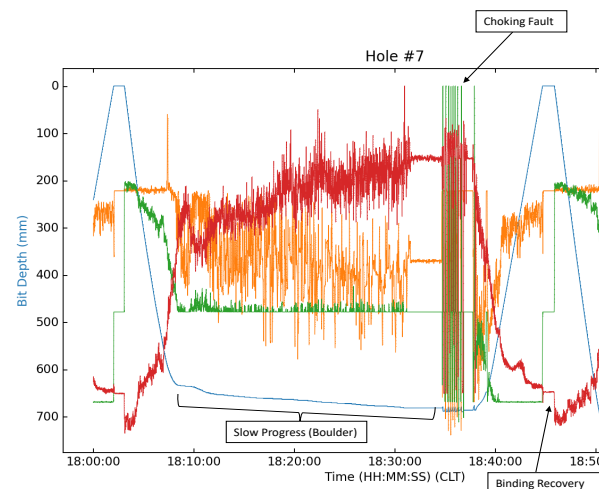
The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) is a rotary-percussive 1m-class drill from Honeybee Robotics intended to begin to work through these issues [1]. It is low-power (rotary and percussive actuators are 200 W each) and lightweight (<20 kg) with the maximum weight on bit limited to 200 N. TRIDENT has been manifested for the Volatiles Investigating Polar Exploration Rover (VIPER) and PRIME-1 lunar south pole missions in 2024 [2], has previously been field tested at a hot, dry analog site in the Atacama Desert [3], and in lunar conditions in thermal vacuum chamber tests [4]. TRIDENT was also part of the 2019 Icebreaker Mars Discovery proposal, as well as in the Mars Life Explorer concept [5]. During ARADS tests, drill control and fault recovery automation software enabled hands-off operations of a rover-mounted TRIDENT drill [3,6].

**TRIDENT Drill Analog Site Validation:** Past TRIDENT tests in thermal vacuum (TVAC) chambers targeted containers of manufactured lunar simulants with added volatiles. 2022 TRIDENT ambient testing at NASA Ames drilled into cemented lunar simulant materials modeled after [7]. Low cuttings-permeability led to cuttings buildup, and drill choking and binding was observed. The Atacama analog site in ARADS [3] had desiccated unconsolidated sediments that did not challenge the TRIDENT design. However, lunar polar regolith is expected to be diverse and heterogeneous with varying clast sizes, with abundant impactites and perhaps subsurface ice deposits. Neither the simulants nor Atacama testing had completely covered the TRIDENT-targeted field characteristics, motivating further analog tests prior to the planned lunar missions.

To gain more insight into the behavior of the TRIDENT hardware in diverse impactites and subsurface ice, and to verify the software automation in that environment, in August 2023 TRIDENT was brought to Haughton Crater, a field analog site in the Canadian Arctic. In September 2023 the same drill was

brought to the Bishop Tuff in southern California to verify whether drilling binding behaviors previously seen in lunar simulant testing would be observed in naturally occurring fine-grained massive layers.

The ~22 Ma Haughton Crater impact structure is located at 75°22' N, 89°41' W, on northwestern Devon Island, Nunavut, Canada. Numerous deposits of pale-grey crater-fill polymictic impact-melt breccia are found within the crater with a typical thickness reaching ~125 m or greater and covering ~60 km<sup>2</sup>. An approximately 600m-thick permafrost layer is also present with ice typically found within 0.5-0.6m of the surface. [8,9] The volcanic tableland north of Bishop, CA exposes densely welded tuff laid down during the eruption that created the Long Valley Caldera at approximately 0.76 Ma. Extensional faults and the Owens River gorge expose cross-sections across the plateau. The area is viewed as an analog site for Mars features believed to be of pyroclastic origin [10, 11, 12].



**Fig. 1.** Slow progress and eventual choking in a subsurface unit at 65-74 cm depth in Haughton Hole 23-7 [13].

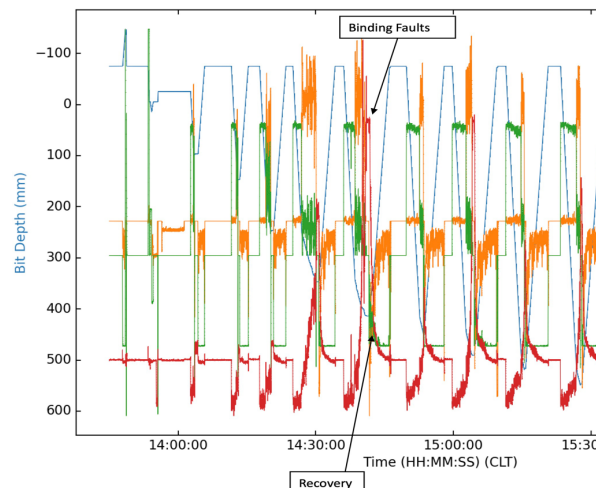
**Results:** *Haughton Crater.* Drilling tests were conducted 8-13 August 2023 at a previously undisturbed area separated 5-10 m from past years' Drill Hill test sites (75.4208, -089.7613) [13]. In six days, TRIDENT drilled 8 holes to nearly 1 m depth each, totaling 7.80 m. The active layer/ice boundary was at ~67 cm depth, with a total of approximately 2.4 m drilled into ice or ice-cemented impact breccia. During drilling, five drill fault states were observed and successfully recovered. Holes 23-1,4 and 7 were drilled under manual control, using Honeybee's Thorax user interface. Holes 23-5, 6, and 8 were drilled with the Ames IBexec automated drilling control software [6].

TRIDENT was observed to have little difficulty in the thawed uncemented impact breccia above the active layer boundary, but required percussion to make slower headway in the ice-cemented breccia. In Hole 23-7 (**Fig. 1**), drilling slowed down in a massive unit just above the active-layer boundary (perhaps a large rock extending into the ice-cementation?), with only 7 cm progress made in 27 minutes of high auger torque and constant percussion, leading to a choking fault and then a binding fault. A similar pattern had been observed in TRIDENT Rio Tinto test data from 2017 [6] as well as in the 2022 laboratory tests.

**Bishop Tuff.** A team from NASA Ames and the US Geological Survey deployed the same TRIDENT drill to Bishop Sites 1B and 1C (37.4203, -118.4289; 37.4265, -118.4215) on 13-16 September 2023, on the Bishop Tuff plateau [14]. A third drill site was used 17-18 September 2023 (37.4598, -118.3667) in an abandoned pumice mine. Four holes (totaling 2.5m depth) were drilled into the fine-grained, meters-thick tuff units at Sites 1B and 1C, and a further two boreholes (totaling 1.98m depth) were made at the pumice site. Drill behavior in the tuff below 10 cm depth was similar to that seen at 65-74 cm depth in Haughton Hole 23-7 (**Fig. 1**) and that seen in the 2022 lab simulant drilling. Drill safety torque limits were exceeded multiple times resulting in drill stops downhole. These freezes then required external added torques (with a pipe wrench) to resume rotation, to unstick the drill for withdrawal. To prevent this choking and binding behavior we found that more-frequent cuttings removal was necessary, e.g., reducing the “drill bite” size from the nominal 10 cm to 2 cm per bite -- bringing the auger up to the surface more frequently, as seen in Bishop Site 1C Hole 2 (**Fig. 2**). This permitted slow progress without drill binding and without external interventions. Conversely, TRIDENT drilling in the more porous pumice target material showed no cuttings buildup issue, and single bites as large as 40 cm were demonstrated.

**Discussion:** We observed that TRIDENT easily penetrated unconsolidated heterogeneous soils (both above the active layer boundary at Haughton and previously in the Atacama). Cemented or consolidated targets that were cuttings-permeable (icy impact breccia, pumice) required more energy applied and percussion. However, in non-cuttings-permeable targets (welded microporous tuff, cemented simulants, Hole 23-7 object) TRIDENT was observed to be prone to excessive cuttings accumulation leading to choking/binding faults and stalling. The wedge cutting bit, used by TRIDENT in field tests and in its flight versions, pulverizes the target rock and creates fine cuttings that ideally are transported up the auger spirals for removal. In porous, fractured or vesicular target materials (such as at the Bishop pumice site) a significant portion of the cuttings are pushed aside, but

for non-fractured, microporous targets the cuttings remain in the borehole and accumulate. Rock powder is relatively incompressible as a working fluid at only 100-200N downward force (TRIDENT limits) and hence eventual drilling progress slows or stops.



**Fig. 2.** Frequent TRIDENT binding and choking faults led to drilling with reduced 2 cm bite sizes at Bishop Tuff sites.

Our recommended strategy for improving TRIDENT cuttings removal in massive target units with low cuttings-permeability is to reduce TRIDENT bite sizes when encountering these units, from 10cm to as little as 1-2cm, to effectively bail the accumulating cuttings. This approach was demonstrated to reduce choking and allowed slow progress to continue in cuttings-impermeable microporous target units (viz. the Bishop tuff in our September 2023 tests or cemented simulants in 2022 ambient tests).

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